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Technologies for Future Precision Strike Missile Systems - Missile/Aircraft Integration

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Abstract/Executive Summary

This paper provides an assessment of the state-of-the-art and design considerations of missile/aircraft integration for future precision strike missile systems. Benefits of missile/aircraft integration include compatibility with a broader range of aircraft carriage platforms, unrestricted carriage envelope, safe and accurate store separation, and enhanced survivability for the aircraft platform. Technologies and design considerations are grouped into the following discussion areas:

- **Missile factor of safety compatibility**. Assessments in this area include structural design factor of safety, carriage flight loads, and design specification of the carriage flight environment.
- **Missile carriage and launch compatibility**. Assessments in this area include launch platform compatibility constraints, firepower, light weight logistics, launcher alternatives, compressed carriage, standard suspension requirements, and safe separation.
- **Survivability (missile observables/insensitive munitions) compatibility.** Assessments in this area include internal carriage, reduced observable plumes, and insensitive munitions.

Introduction

Missile/aircraft integration sets constraints on the missile that must be considered early in the design development process, as illustrated in Figure 1. Moreover, the design process requires iteration to harmonize the outputs from the diverse areas of mission/scenario definition, missile requirements, aircraft integration, missile concepts, and technologies. In a few cases it may be possible to modify a launch platform to accommodate a new missile, but in most cases this is not an option. Generally the launch platform is a constraint that drives the missile design. For example, AMRAAM was originally developed as a light weight radar missile for carriage on the wing tips of the F-16, which has a 300 pound weight limit. Later, AMRAAM was modified to a compressed carriage configuration (clipped wings and tails) to better accommodate internal carriage in the F-22 center weapons bay. Precision strike missiles are driven as much by launch platform compatibility as other measures of merit. Weapon compatibility with all launch platforms has high payoff in the neckdown benefit cost savings of fewer missile logistics systems.

Figure 2 shows an example of how missile/aircraft integration impacts the design validation/technology development process. Launch platform integration is considered from the start of subsystem development activities, continuing as they evolve into a missile system. In the propulsion area, static firings and insensitive munition tests are conducted before a missile with a live rocket motor is fired from a launch aircraft. In the airframe area, wind tunnel testing includes not only the basic aerodynamic configuration development, but also store separation wind tunnel tests. In the guidance & control area, the flight control system sensors, actuators, and electronics are analyzed to ensure safe separation as part of a missile modeling and simulation activity. The laboratory tests include environmental tests that simulate the operational temperature and vibration. The missile modeling and simulation activities include safe separation analysis. Similar to the propulsion area, the warhead has insensitive munition tests prior to firing a missile with a live warhead from an aircraft.

The flight test progression is shown on the far right of Figure 2. Flight test validation is a progressive activity of increasing complexity. The objective of progressive testing is to minimize risk and enhance safety in the flight test activity. A typical progression of flight testing begins with captive carry and ends with live warhead launches. Intermediate tests are store jettison tests, safe separation tests, unpowered guided flights with an inert warhead, powered guided flights with an inert warhead, and finally, all-up powered guided flights with a live warhead.

A summary of the subsystem technologies for precision strike missiles that relate to missile/aircraft integration is given in Figure 3. In addition to subsystem technologies, considerations such as structure design, carriage environment, geometry/weight constraints of the aircraft, aircraft launcher requirements, and aircraft survivability also drive missile/aircraft integration. Many of the technologies in the figure are covered in this paper, however there is not sufficient time to address them all. A summary of other technologies is presented in the Introduction/Overview paper of this lecture series.

Missile Factor of Safety Compatibility

This assessment of missile factor of safety compatibility addresses the design considerations of structural design factor of safety, process for defining the missile structure design for compatibility with carriage flight loads, and design specification of the carriage flight environment.

Structural design factor of safety. Missile structure/aircraft integration includes the factor of safety considerations for manned operation. Typical factors of safety for tactical missiles are shown in Figure 4. The factor of safety tends to be high where there is human danger involved. As an example, pressure bottle ultimate and yield factors as safety are typically 2.5 and 1.5 respectively. Missile gas bottles can be pressurized up to 10,000 psi. Because gas bottles require periodic logistics maintenance and inspection by ground personnel, the factor of safety is high. Another area where the factor safety is high is in the area of ground handling loads, such as cross-country transportation. Factors of safety for ground handling loads are 1.5 ultimate loads and 1.15 in yield loads. Other examples of high factor of safety are captive carriage and separation. During carriage or during aircraft separation, missile factors of safety are required to be about 1.5 for ultimate and 1.15 for yield. The motor case is designed not only for conditions of environmental extremes, such as a hot day, but also for consideration of pilot safety. The ultimate and yield factors of safety for motor maximum effective operating pressure are about 1.5 and 1.1 respectively. The required factors of safety are lower for flight conditions where the missile is safely away from the launch aircraft. For example, missile free flight loads factors of safety are about 1.25 and 1.1 respectively and the thermal loads, which occur near the end of flight, are just design considerations with a factor of safety of 1.0. A distinguishing characteristic of precision strike missiles is lower factor of safety compared to manned aircraft or even unmanned air vehicles (UAVs). Since missiles are a throw-away, the factor of safety can be reduced if there is no human danger involved, resulting in lighter weight compared to an aircraft or a UAV. It is noted that an additional factor of safety is required for structural areas where there is relatively large uncertainty. An example is castings, which can have hidden voids, requiring an incremental factor of safety of about 1.25 in addition to the normal design factors of safety. Fittings also require an additional factor of safety of about 1.15 because of the uncertainty in the analysis for attachment integrity. The applicable military standards in the U.S. that are considered in factors of safety include environmental (HDBK-310, NATO STANAG 4370, MIL-STD-810F, MIL-1670A), strength and rigidity (MIL-STD-8856), and captive carriage (MIL-STD-8591) military standards.

Because high performance missiles such as ramjets are severely weight and volume limited, there is high leverage in improving performance if the required factor of safety could be reduced. Technology in improved analysis and development tools will provide reductions in missile weight and cost by reducing the design uncertainty and the required factor of safety. An example is Micro-machined Electro-Mechanical Systems (MEMS) technology. MEMS devices are fabricated from a single piece of silicon by semiconductor manufacturing processes, resulting in a small, low-cost package (see Figure 5). For example, between 2,000 and 5,000 MEMS sensor devices are produced from a single five-inch silicon wafer. Future precision strike missiles will have low cost/small size MEMS sensors for data collection during missile development and for health monitoring after production. Localized stress/strain, vibration, acoustics, temperature, pressure, and

other environmental conditions can be monitored through sensors scattered around the airframe. The higher confidence due to MEMS data will allow weight reduction in the over designed structure.

Carriage flight loads. Flight carriage impact on missile design is illustrated in Figure 6. A comparison is shown of a representative distribution of missile free flight maneuver loads versus launch platform carriage loads. The left section of the figure shows a typical free flight maneuvering air load distribution and the weight load distribution on each bulkhead. The right section of the figure shows a typical maneuvering aircraft carriage air load distribution, carriage weight load distribution, and carriage suspension loads. The missile free flight loads are usually higher than the carriage loads because missile maximum maneuverability is usually greater than that of aircraft. The missile skin thickness is usually not sized by aircraft maneuver loads. As shown in the right section of the figure, carriage loads are taken out through a suspension system. It is usually possible to get a fairly accurate prediction of the missile free flight loads. Also, wind tunnel tests are usually conducted to determine free flight air loads. Unfortunately, this is usually not the case for carriage flight loads, as it is difficult to accurately predict the two-body problem of a store in the flow field of the launch aircraft. In addition, it is difficult to get accurate wind tunnel data, due to the small size of the missile model for aircraft carriage wind tunnel tests. As a result, the current approach to estimating carriage loads is usually based on the conservative process of Military Standard (MIL STD) MIL-A-8591. As missile loads estimation becomes more accurate in the future, there is a potential for structure weight savings, based on improving the estimation accuracy for carriage loads.

Design specification of the carriage flight environment. Air launched precision strike missiles must have sufficient robustness in their design to accommodate a broad flight environment during carriage. Table 1 has examples of environmental requirements for storage and aircraft carriage temperature, humidity, rain, wind, salt fog, vibration, shock, and acoustics. An example of concern at the temperature extremes is propulsion and warhead safety, reliability, and performance. Another example is high rain rate. Rain is a particular concern for dome erosion at high carriage velocity. A third example is corrosion from salt fog, particularly for naval operation. An advantage of internal bay carriage over external carriage is that many of the carriage environment concerns are alleviated. However, some carriage environment concerns could be greater for internal carriage than that of external carriage. Examples include high vibration and acoustic loads when the carriage bay doors are open at a flight condition with high dynamic pressure.

Missile Carriage and Launch Compatibility

This assessment of missile carriage and launch compatibility addresses the design considerations of launch platform compatibility constraints, firepower, light weight logistics, launcher alternatives, compressed carriage, standard suspension requirements, and safe separation. New technology development for weapon compatibility and high firepower includes low volume missile propulsion, ordnance and airframe; store carriage and store separation wind tunnel tests; computational fluid dynamics (CFD) predictions; and finite element modeling (FEM) predictions.

Launch platform compatibility constraints. Carriage constraints for missiles on surface ships, submarines, and aircraft are shown in Figure 7. Cross-platform compatibility is desirable for a missile system. A larger total buy of missiles for cross-platform application has benefits of lower unit production cost and lower logistics cost. In the United States, the Vertical Launch System (VLS) is a standard carriage and launch system for missiles on surface ships. The VLS geometry constraints are 22 inches x 22 inches x 256 inches. The maximum weight constraint is 3,400 pounds. United States submarines have a similar standard launcher that is circular in cross section. The submarine Canister Launch System (CLS) has a diameter constraint of 22 inches and a length constraint of 256 inches. Maximum missile weight for the CLS is the same as that of the VLS, 3,400 pounds. The VLS and CLS also have a maximum limit on the total impulse delivered in the event of hangfire, to avoid burning through the launch platform structure. Finally, aircraft launch platforms for missiles include tactical fighters, bombers, helicopters, and UCAVs. Shown in the figure is an example of a fighter aircraft, the F-18C. The F-18C carries weapons externally on pylons and rails. Other aircraft, such as the F-22, RAH-66 and B-1, have an additional capability of internal carriage. Internal launchers include vertical ejection, rail trapeze, and rotary ejection. Missile span constraint for aircraft carriage is about 24 inches x 24 inches. Length constraint is about 168 inches and the maximum allowable missile weight varies

from about 500 to 3,000 pounds, depending upon the aircraft. There is a desire for lighter weight missiles to maximize the firepower of small aircraft such as the F-18C, Comanche, and Predator. As an example, 50 percent of the U.S. Navy fleet combat aircraft in the year 2010 time frame are expected to be F-18Cs.

Firepower. Figure 8 shows how day/night operation, firepower objectives, and weapons loadout affect the maximum allowable weight of a precision strike missile. Shown are examples of the F-18C and F-18E aircraft. Note that the F-18C aircraft has less capability than the F-18E in all loadout configurations. Figure 8 shows a large difference in maximum allowable missile weight for day versus night operation. The difference is due to the additional fuel that must be reserved for night operation off an aircraft carrier. The maximum weapon weight shown in the curves must also be reduced to account for limits in asymmetric carriage (2,500 lb for inboard carriage and 1,500 lb for outboard carriage). Finally, note the reduction in maximum allowable missile weight as the loadout configuration is changed from a clean aircraft with precision strike missile(s) to other configurations. Five other loadout configurations are the precision strike missile(s) plus 1) a centerline fuel tank, 2) two inboard fuel tanks, 3) centerline fuel tank plus two Sidewinder air-to-air missiles, 4) centerline fuel tank plus two anti-radiation missiles (ARM), and 5) two inboard fuel tanks plus two Sidewinders. The maximum allowable weight of a single precision strike missile on the F-18E is about 4,800 lb under ideal conditions. For an F-18C operating at night with two inboard fuel tanks and two Sidewinders, the maximum allowable weight of a precision strike missile is much lower, about 1,800 lb. In the case of carriage of two precision strike missiles, the F-18E under ideal conditions can carry a missile weighing up to 2,400 lb. At the other extreme for an F-18C loadout of two precision strike missiles, operating at night with the addition of two inboard fuel tanks and two Sidewinders requires that the precision strike missile weigh less than 900 lb. A precision strike missile weight of about 1,400 lb is probably a good compromise for the example of F-18C/E aircraft integration. It allows two weapons on the F-18C for unrestricted day operation, two weapons on the F-18E for near unrestricted night operation, and three weapons on the F-18E for day operation with two inboard fuel tanks.

Light Weight Missile Logistics. Shown in Figure 9 are examples of the impact of missile weight on the support manpower requirements for tactical missiles. A typical maximum lift requirement per person is between 50 to 100 pounds. For a man portable missile such as the 50-pound Javelin system, a single gunner can prepare and launch the missile. As an example of a moderately heavy missile, the 190-pound Sidewinder requires two-to-four personnel to install the missile on the launch aircraft. A heavier missile, such as a 500-pound Sparrow, requires additional support personnel plus ground support equipment. Finally, a very heavy weapon, such as a laser guided bomb, requires specialized, heavy ground support equipment.

Compressed carriage. A missile that has reduced span surfaces during carriage allows closer spacing of the adjacent missiles on the launch platform. Approaches for compressed carriage include reduced span/longer chord surfaces, folded surfaces, wraparound surfaces, and switch blade surfaces. Figure 10 illustrates the benefits of compressed carriage. The F-22 internal center weapons bay typically has two partitions, with one partition for air-to-air (e.g., AMRAAM) missiles. A baseline AMRAAM loadout in an F-22 center bay partition allows two missiles per partition. However, compressed carriage AMRAAM can be packaged three missiles per partition, a 50 percent increase in the firepower load-out. For an air-to-air mission only, both partitions of the F-22 center bay are allocated to air-to-air missiles, allowing a bay loadout of six compressed carriage AMRAAMs.

Launcher integration. Figure 11 shows examples of missile carriage on U.S. standard rail and ejection launchers. In the upper left is an AGM-114 Hellfire II missile on a helicopter rail launcher. Rail launchers are particularly suited to light weight, high thrust missiles such as Hellfire. Hellfire weighs 100 lb, with a launch thrust-to-weight of about 30:1. Hellfire has a laser seeker with +/- 30 degrees field of regard. A launch platform integration consideration is that the missile must be mounted sufficiently far forward on the aircraft such that the seeker line-of-sight to the target is not obscured by the launch platform. Another concern for rail launch is the effect of tip off error on the missile miss distance at the minimum effective range. A rail-launched missile has roll, pitch and yaw rate excursions as it moves down the rail, due to missile/rail clearances and the aeroelasticity of the launcher. Tip off error at launch has an effect on the missile miss distance at its minimum effective range. Another contributor to missile miss distance at the minimum effective range is the effect of helicopter downwash on the missile angle of attack at launch. In the upper right

corner of Figure 11 is an AGM-88 HARM missile. Most precision strike missiles, including HARM, use ejection launch. HARM has an anti-radiation homing seeker. The installation pylon must also be sufficiently far forward on the aircraft that the seeker line-of-sight to the target is not obscured by the launch platform. The pylon contains ejection cartridges that provide downward velocity and pitch rate to the missile at launch, aiding safe and accurate separation. Suspension of the missile is such that the missile center-of-gravity is midway between the ejectors. A concern during launch is the aircraft local angle of attack and local angle of sideslip effects on the missile flight trajectory. Finally, the bottom of Figure 11 shows an example of internal carriage. Eight AGM-69 SRAM missiles are shown on a bomber rotary launcher. The missiles are ejected from the bay at an ejection velocity of about 20 ft/sec. Concerns for internal bay carriage include bay acoustics, bay vibration, and flow field angularities near the aircraft.

Standard suspension requirements. Store suspension requirements for ejection launchers, based on US MIL-STD-8591 are summarized in Table 2. Shown are store weight and parameters for light weight stores (up to 100 lb), medium weight stores (101 to 1,450 lb), and heavy weight stores (over 1,451 lb). Suspension alternatives are 30-inch and 14-inch suspension systems. For an ejected store weight up to 100 lb, only the 14-inch suspension can be used. For a light weight missile on the 14-inch suspension, the lug height and minimum ejector pad area are prescribed as 0.75 inch and 4.0 in x 26.0 in respectively. For a medium weight missile, with a weight between 101 and 1,450 lb, either the 14-inch suspension or a 30-inch suspension may be used. Medium weight ejected stores have larger required lug height and minimum ejector area. They also require lug wells. The required lug wells could have a strong impact on the missile internal structure design. For example, in some cases the rocket motor overlaps the missile center of gravity, and it may be difficult to accommodate lug wells in the rocket motor case. A strong back may be required, similar to that of the AGM-69 SRAM missile. For a heavy missile with a weight over 1,451 lb, only the 30-inch suspension can be used. MIL-STD-8591 requires that the lugs have a deeper well if the missile weighs more than 1,451 lb.

Examples of missile rail launchers that are compatible with MIL-STD-8591 are shown in Figure 12. Rail launchers usually suspend the missile at two locations, a forward hanger and an aft hanger. Some rail launchers suspend the missile at three locations, for added stiffness. The launcher shown in the top of the figure is the LAU-7. The LAU-7 rail launcher has a store weight limit of 300 pounds and a store diameter limit of 7 inches. The LAU-7 is a standard launcher for the Sidewinder missile. It has forward and aft hangers with a shoe width of 2.26 inches. The LAU-117 rail launcher, shown in the bottom of the figure, has a store weight limit of 600 pounds and a store diameter limit of 10 inches. The LAU-117 is a standard launcher for the Maverick missile. It has a forward hanger with a shoe width of 1.14 inches and an aft hanger with a shoe width of 7.23 inches.

Safe Separation. Aircraft store compatibility wind tunnel tests are conducted to determine store carriage loads and store separation forces, moments, and trajectories. Figure 13 shows wind tunnel installations of aircraft and store models. Note that a typical aircraft store load-out has closely spaced stores. The local airflow around a store is difficult to predict. There is a complex flow field interaction of a store with the aircraft and also with the adjacent stores.

The types of wind tunnel testing for store compatibility include:
- Flow field mapping with a pitot static pressure probe to measure the local static pressure, total pressure, and angle of attack
- Flow field mapping with an instrumented store model on a sting to measure the forces and moments on the store immersed in the aircraft flow field
- Captive trajectory simulation of an instrumented store model on a sting
- Drop testing of store models. The store models models are constructed of lead, tungsten, or even gold to provide weight scaling to simulate full-scale buoyancy in the wind tunnel test.

Examples are shown in Figure 14 of safe separation of a rail launched AMRAAM from an F-16 and the clean separation of two laser guided bombs dropped from an F-117. In the bottom right corner is a photograph showing the clean separation of a rapid bomb drop from the B-2 bomber. A rapid bomb drop is desirable to

minimize the exposure time with the high observables from the open weapon bay. Exposure time less than ten seconds is desirable to prevent threat radars from establishing a track file.

Survivability (Missile Observables and Insensitive Munitions) Compatibility

This assessment of survivability (missile observables and insensitive munitions) compatibility addresses the design considerations of internal carriage, reduced observable plumes, and insensitive munitions.

Internal carriage. Alternative approaches for missile carriage include conventional external carriage, conformal carriage, and internal carriage. Conventional external carriage has disadvantages of high radar cross section (RCS), high carriage drag, and potentially adverse aeroelastic, stability, and control interactions with the aircraft platform. Conformal carriage has an advantage of reduced RCS and drag compared to conventional carriage. However, the preferred approach for the lowest carriage RCS and the lowest drag is internal carriage. Figure 15 shows examples of internal carriage and loadouts for low observable fighters, bombers, and helicopters. In the upper left is shown the F-22 internal center bay. The F-22 center bay typically has an outboard partition for air-to-air weapons (e.g., AMRAAMs) and an inboard partition for air-to-surface weapons (e.g., JDAM). LAU-142/A pneudraulic (pneumatic plus hydraulic) ejection launchers are provided for the AMRAAMs. The LAU-142 has a nine-inch stroke that ejects an AMRAAM from the bay at a velocity of 25 feet per second. The peak ejection acceleration is 40 g. Advantages of pneudraulic ejection compared to conventional pyrotechnic cartridge ejection include less logistics, faster turnaround for weapon loading, and a more nearly constant ejection force that allows a shorter ejection stroke. A conventional BRU-46/A bomb rack is provided for the GBU-32 JDAM (1,000-pound class weapon). Examples of typical mixed weapon loadouts in the F-22 center bay are (1) two AMRAAMs (without compressed carriage) plus one 1,000 pound JDAM, or (2) three compressed carriage AMRAAMs plus one 1,000 pound JDAM. The F-22 center bay can also be set up for air-to-air weapons only, such as four conventional AMRAAMs (without ompressed carriage) or six compressed carriage AMRAAMs. The F-117 internal weapons bay is shown in the top center of the figure. The F-117 weapons bay is similar to that of the F-22, except that it has about twice the payload weight capability. A typical loadout for the F-117 is two Paveway guided bombs (2,000 pound class). Shown in the figure foreground is the GBU-27 laser guided bomb. Its warhead is based on the BLU-109 hardened structures penetrator bomb. In the background is the GBU-10 laser guided bomb. Its warhead is either the general-purpose Mk-84 bomb or the BLU-109 penetrator bomb. The B-1 bomber weapons bay is shown in the upper right of the figure. The B-1 has three bays. Each bay has a rotary launcher for ejection of missiles and bombs. An Ejector Rack Assembly for each weapon is attached to the rotary launcher. The Ejector Rack Assembly has a thirty-inch spacing of the ejectors. Shown in the figure is a standard loadout of eight AGM-69s per bay. In the lower left section of the figure is a photograph of an F-22 side bay. The F-22 has two side carriage bays. Each bay is capable of carrying a single Sidewinder missile on a LAU-141/A trapeze rail launcher. A trapeze launcher is required for lock-on before launch missiles. During the launch sequence the trapeze launcher extends the missile away from the aircraft, the missile seeker acquires the target, and the missile is launched. It is noted that the LAU-141/A launcher has a deflector surface to keep the motor plume from entering the weapon bay. Finally, the lower right section of the figure is a photograph of the RAH-66 Comanche helicopter. The Comanche has two side bays with rail launchers. Each bay has a typical mixed mission (combined air-to-surface/air-to-air) loadout of one Hellfire missile plus two Stinger missiles plus four Hydra 70 rockets. For an air-to-surface only mission, each bay can carry three Hellfire missiles, giving the Comanche a total bay loadout of six Hellfire missiles. As shown in the figure, the Comanche can also carry eight Hellfire missiles externally, at the expense of increased RCS.

Reduced observable plumes. Table 3 shows tradeoffs of rocket motor performance versus safety and observable concerns. The highest performance propellants unfortunately also have high observable smoke particles (e.g., Al_2O_3), due to metal fuels such as aluminum. An initial approach to reduce plume observables is reduced smoke motors. Reduced smoke motors replace the metal fuel with a binder fuel such as hydroxyl terminated polybutadiene binder (HTPB). The performance and insensitive munition capability of a reduced smoke motor is slightly lower than that of a high smoke motor. Reduced smoke propellants can still have visual observables from a hydrogen chloride contrail. The HCl contrail occurs at low atmospheric temperature. A third type of propellant is minimum smoke propellant. Minimum smoke propellants eliminate the HCl contrail by eliminating ammonium perchlorate as an oxidizer, resulting in lower visual observables.

The performance and safety of current minimum smoke propellants is not as good as that of high smoke propellants. Current minimum smoke propellants are cross-linked double base (XLDB) propellants. In the older minimum smoke double-base propellants, the propellant consists generally of cotton (cellulose) combined with nitric acid to form nitrocellulose (guncotton), which in turn is combined with nitroglycerin, another fuel-oxidizer. In the double-base propellant, the nitrocellulose serves as the binder, and the nitroglycerin causes it to solidify. Examples of current minimum smoke propellants are HMX (cyclotetramethylene tetranitramine) and RDX (cyclotrimethylene trinitramine). An example of a new minimum smoke propellant is the US Navy China Lake CL-20 propellant. CL-20 is a cyclic polynitramine, with a unique caged structure that provides higher crystal density, heat of formation, and oxidizer-to-fuel ratio. CL-20 propellant has 10-to-20 percent higher performance than HMX and RDX. CL-20 also has reduced shock sensitivity (Class 1.3 versus 1.1) and milder cookoff reaction than either HMX or RDX. A disadvantage of CL-20 propellant is high cost (currently more than $400 per pound). Another example of a new minimum smoke propellant developed by Russia is Ammonium Dinitramine (ADN). ADN performance and cost are similar to that of CL-20.

Figure 16 illustrates the plume observables of high smoke, reduced smoke, and minimum smoke propellants. The relatively old Sparrow missile rocket motor is a representative high smoke motor. The high smoke plume is shown in the upper left corner of the figure. Sparrow has high smoke Al_2O_3 particles from aluminum fuel. Shown in the upper center of the figure is an example of a reduced smoke rocket motor. AMRAAM is a more recent missile, with a reduced smoke motor. It still has a contrail of HCl from the ammonium perchlorate oxidizer. The HCl contrail occurs if the atmospheric temperature is less than -10° Fahrenheit, corresponding to altitudes greater than about 20,000 feet. Finally, the far upper right photograph is an example of a minimum smoke rocket motor. Javelin is a recent missile with a minimum smoke motor. It has almost no smoke from either the launch motor or the flight motor, enhancing the survivability of the gunner. Minimum smoke propellants can have an H_2O (ice) contrail if the atmospheric temperature is less than -35° Fahrenheit, corresponding to altitudes greater than about 27,000 feet.

The bottom left section of the figure shows typical contrails for high smoke, reduced smoke, and minimum smoke motors. The high smoke motor solid particles are visible immediately behind the nozzle under all atmospheric conditions. The contrail from a reduced smoke motor occurs farther downstream of the nozzle. It is produced when the HCl gas from the reduced smoke motor is absorbed by water and then freezes at low atmospheric temperature. Finally, water vapor from a minimum smoke motor can also freeze farther downstream of the nozzle to produce a contrail at low atmospheric temperature.

Insensitive Munitions. Insensitive munitions have high payoff in improving launch platform survivability. The critical subsystems are the rocket motor propellant/engine fuel and the warhead. In the U.S. the design considerations for insensitive munitions are based on MIL-STD-2105B. MIL-STD-2105B includes design considerations of hardening against threat weapons, safety from fire, dropping the weapon, extremes in environmental temperature, missile vibration, and operation off an aircraft carrier. Hardening against threat weapons includes considerations of fragment impact and blast. Cookoff from a fire includes the type of fire (slow cookoff, fast cookoff) and the warhead or rocket motor reaction to the fire (e.g., burning, detonation). Drop shock sensitivity consideration is a particular concern for ground maintenance personnel dropping the missile during handling. The environmental temperature consideration includes both very low temperatures that could damage the rocket motor and very high temperatures that could cause detonation of the warhead or rocket motor. Missile vibration consideration includes the dynamic acceleration imparted by carriage on the launch platform. Finally, aircraft carrier operation includes the shock of aircraft landing sink rates as high as 18 ft/sec.
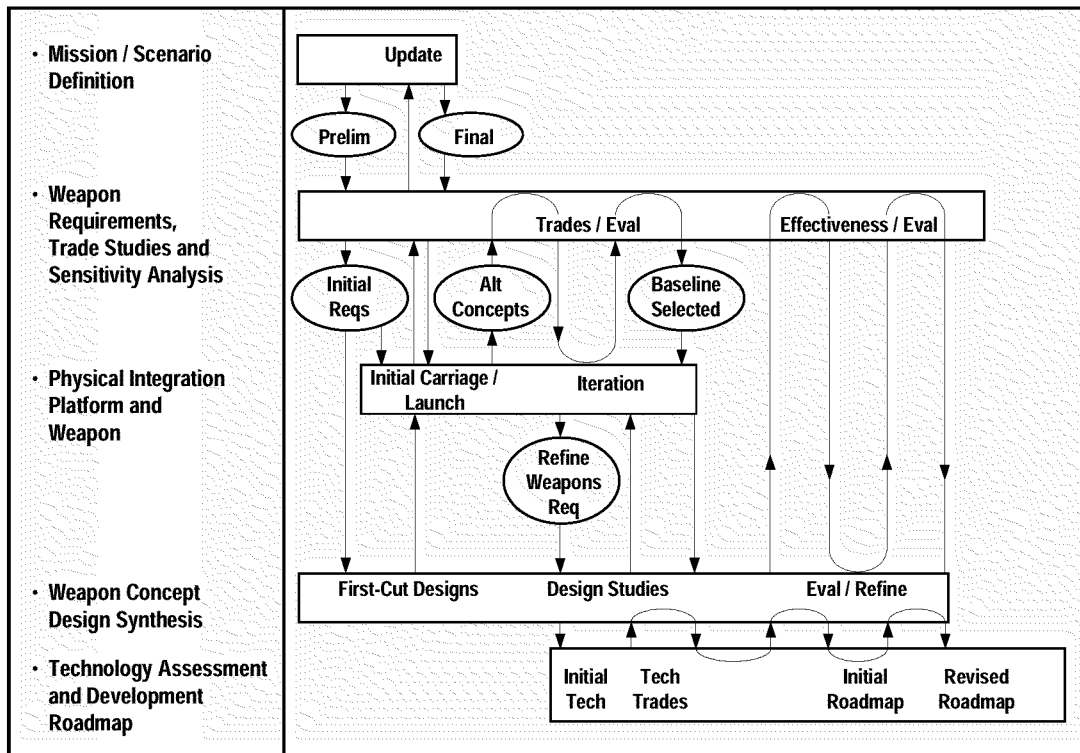
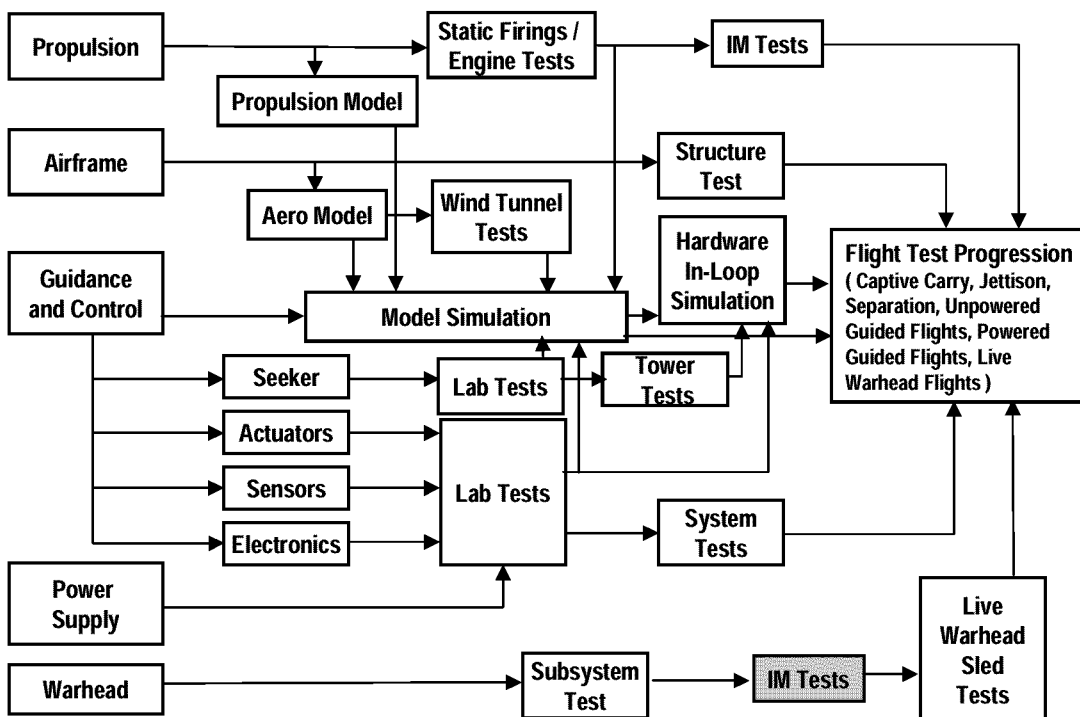Figure 1. Launch Platform Integration Provides Constraints in Missile Design.

Figure 2. Air Launched Precision Strike Missile Development Leads to Aircraft Flight Test Validation
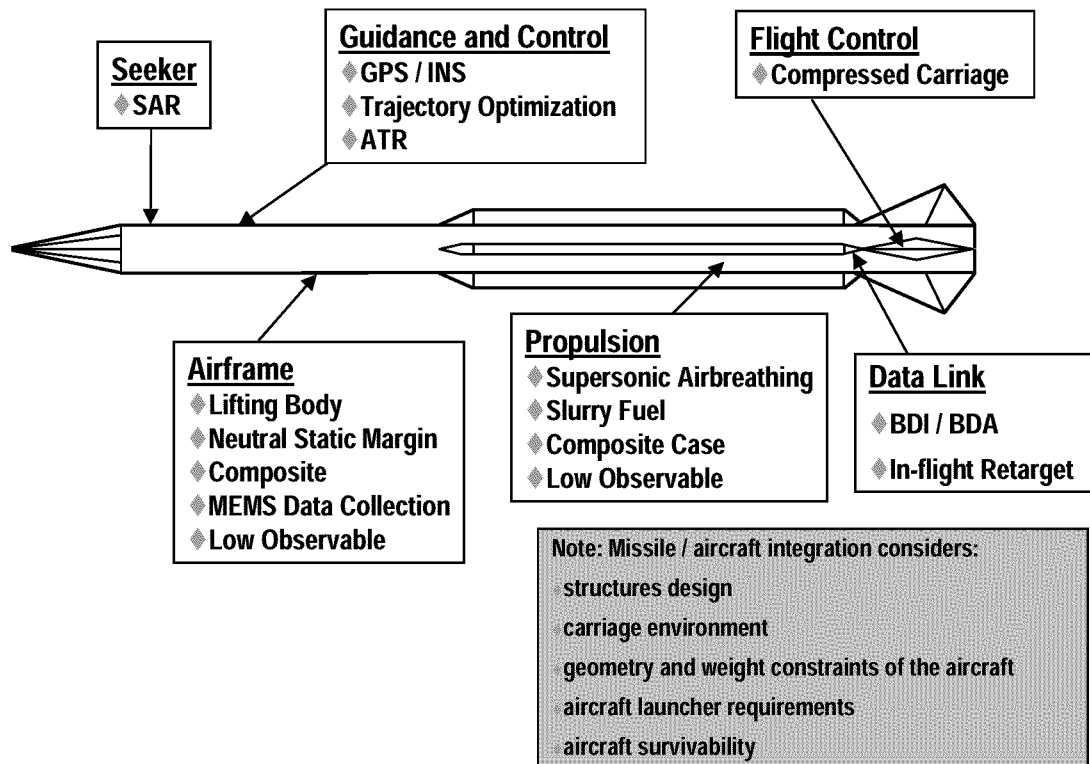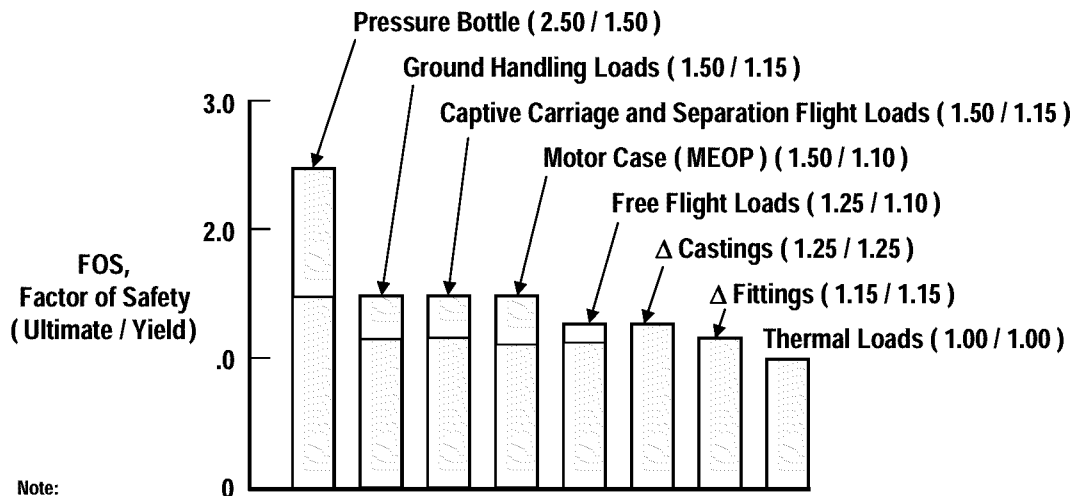
Seeker
◆ SAR

Guidance and Control
◆ GPS / INS
◆ Trajectory Optimization
◆ ATR

Flight Control
◆ Compressed Carriage

Airframe
◆ Lifting Body
◆ Neutral Static Margin
◆ Composite
◆ MEMS Data Collection
◆ Low Observable

Propulsion
◆ Supersonic Airbreathing
◆ Slurry Fuel
◆ Composite Case
◆ Low Observable

Data Link
◆ BDI / BDA
◆ In-flight Retarget

Note: Missile / aircraft integration considers:
◆ structures design
◆ carriage environment
◆ geometry and weight constraints of the aircraft
◆ aircraft launcher requirements
◆ aircraft survivability

Figure 3. New Precision Strike Missile Technologies That Impact Aircraft Integration.

Pressure Bottle (2.50 / 1.50)
Ground Handling Loads (1.50 / 1.15)
Captive Carriage and Separation Flight Loads (1.50 / 1.15)
Motor Case (MEOP) (1.50 / 1.10)
Free Flight Loads (1.25 / 1.10)
Δ Castings (1.25 / 1.25)
Δ Fittings (1.15 / 1.15)
Thermal Loads (1.00 / 1.00)

FOS,
Factor of Safety
(Ultimate / Yield)

3.0
2.0
.0
0

Note:
·MIL STDs include environmental (HDBK-310, NATO STANAG 4370, 810F, 1670A), strength and rigidity (8856), and captive carriage (8591).
·The entire environment (e.g., storage, ground handling, captive carriage, launch separation, post-launch maneuvering, terminal maneuvering) must be examined for driving conditions in structure design.
· Δ Castings is expected to be reduced in future as casting technology matures.
· Reduction in required factor of safety is expected as analysis accuracy improves will result in reduced missile weight / cost.

Figure 4. Missile Structural Design Is Driven by Safety.

◆Micro-machined Electro-Mechanical Systems (MEMS)

- ◆Small size / low cost
- ◆Semiconductor manufacturing process
- ◆2,000 to 5,000 sensors on a 5 inch silicon wafer

◆Missile Development Application

- ◆Data Collection and Health Monitoring

◆Distributed Sensors Over Missile

- ◆Stress / strain
- ◆Vibration
- ◆Acoustics
- ◆Temperature
- ◆Pressure

◆Allows Reduced Design Uncertainty / Factor of Safety

- ◆Provides reduced weight and cost

Figure 5. Small Size MEMS Sensors Can Reduce Required Factor of Safety, Saving Missile Weight.
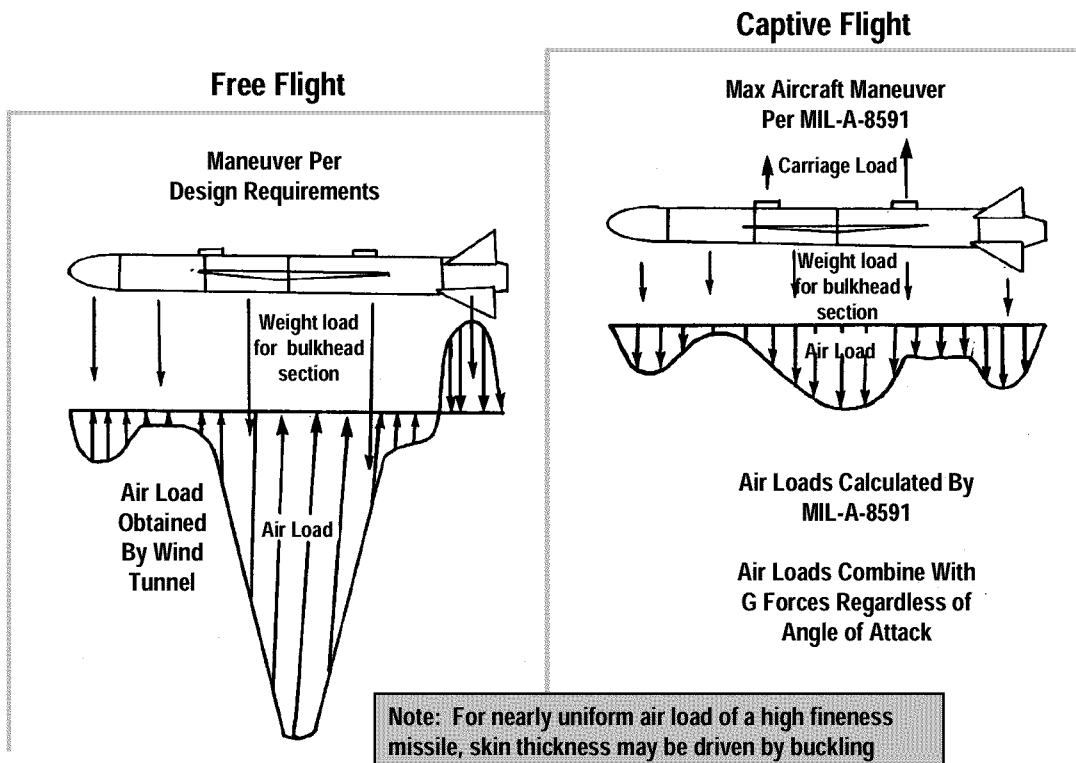
Figure 6. Process for Captive and Free Flight Loads Calculation.

Table 1. Robustness Is Required to Satisfy Storage and Aircraft Carriage Environmental Requirements.

Environmental Parameter	Example of Environmental Requirement
◈ Temperature	-60°F to 160°F
◈ Humidity	5% to 100%
◈ Rain	120 mm / hr
◈ Wind	100 km / hr steady
	150 km / hr gusts
◈ Salt fog	3 grams / mm² per year
◈ Vibration	10 g rms
	MIL STD 810, 648, 1670A
◈ Shock	Drop height 0.5 m
	100 g 10 ms, half sine wave
	MIL STD 810, 1670A
◈ Acoustic	160 dB
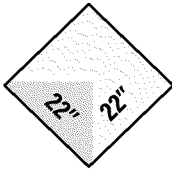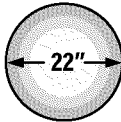
Launch Platform	Launcher				Maximum Body Shape	Maximum Length	Maximum Weight
Surface Ships	Surface VLS				Square Missile (22" × 22")	256"	3400 lb
Submarines	Sub-CLS				Round Missile (22")	256"	3400 lb
Aircraft	External Rail / Eject	Internal Vert Eject	Internal Trap Rail	Internal Rotary	~24" x 24"	~168"	~500 lb to 3000 lb

Figure 7. Missile Shape, Size, and Weight Are Driven by Launch Platform Compatibility.
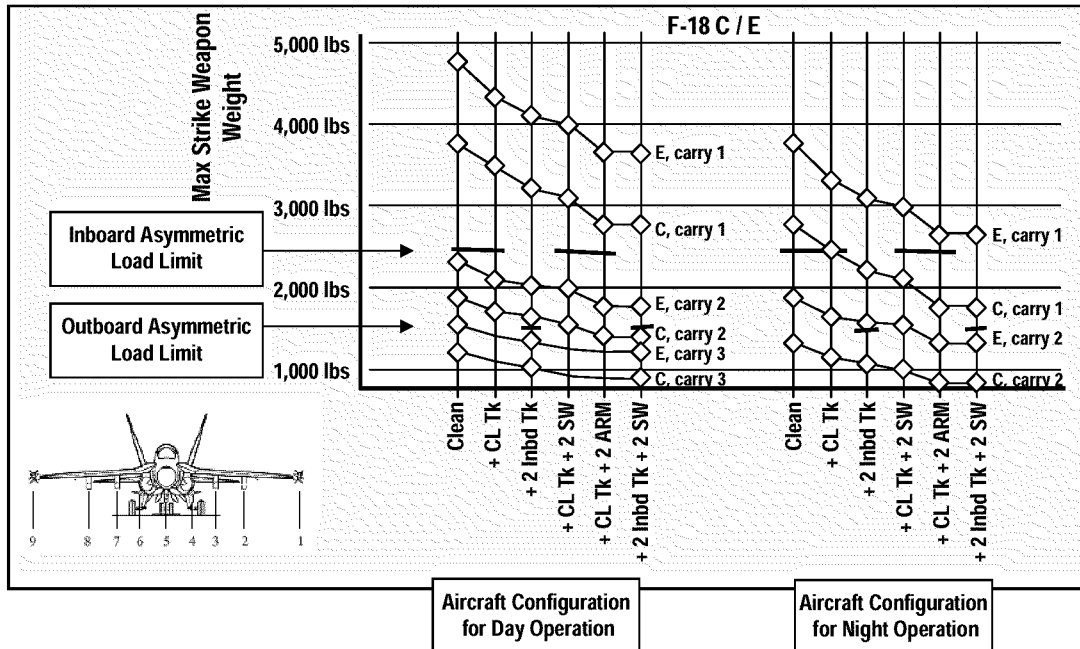
Figure 8. Light Missiles Enhance Firepower.
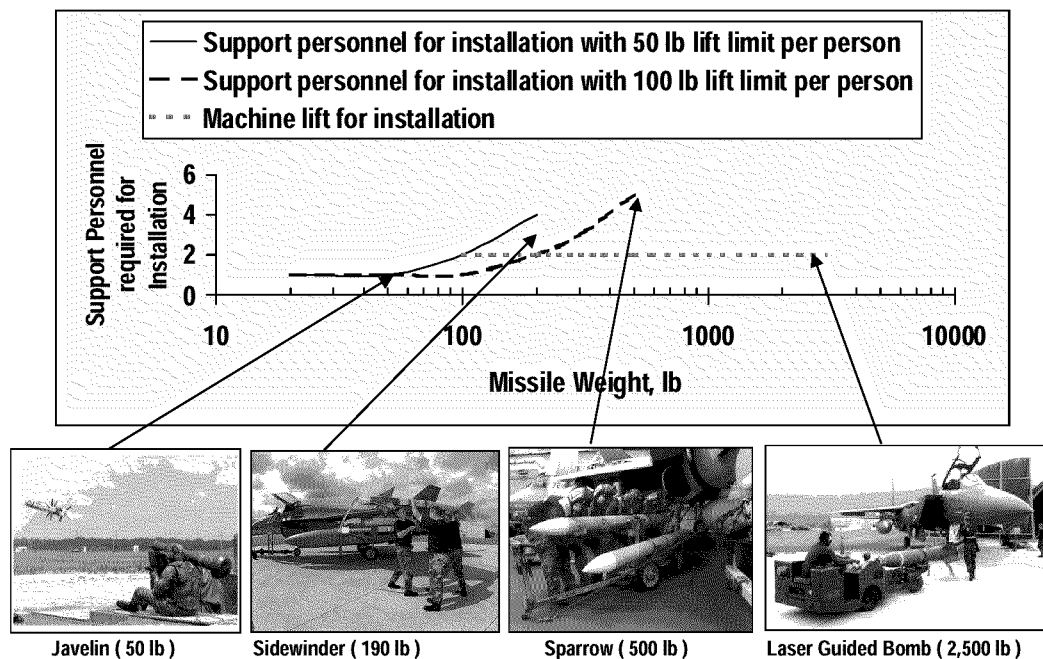
Figure 9. Logistics Is Simpler for Light Weight Missiles.

Baseline AMRAAM

Compressed Carriage AMRAAM (Reduced Span Wing / Tail)

Baseline AMRAAM:
Loadout of 2 AMRAAMs
per Semi-Bay

17.5 in   17.5 in

Compressed Carriage
AMRAAM: Loadout of 3
AMRAAMs per Semi-Bay

12.5 in   12.5 in   12.5 in

> Alternative approaches to compressed carriage include surfaces with small span / longer chord, folded surfaces, wrap around surfaces, and switch blade surfaces.

Figure 10. Compressed Carriage Missiles Provide Higher Firepower for
Aircraft with Internal Weapon Bays.

AGM-114 Hellfire: Helicopter Rail Launcher
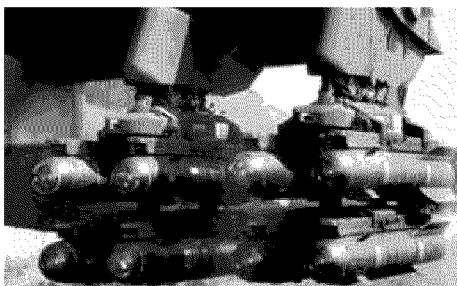
AGM-88 HARM: Fighter Ejection Launcher
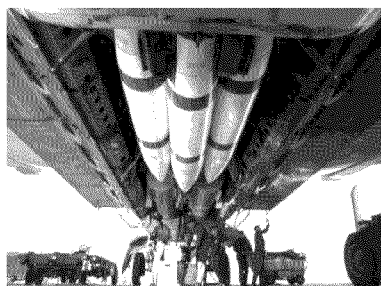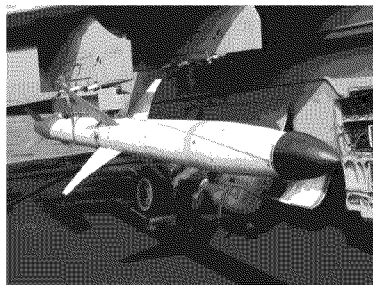
AGM-69 SRAM: Bomber Rotary Launcher

Missile / Aircraft integration Launch Considerations

◆ Seeker field of regard ⇒ aircraft not obscuring

◆ Launch rail clearance ⇒ miss at min range

◆ Launcher aeroelasticity ⇒ miss at min range

◆ Aircraft local flow field α, β ⇒ safe separation

◆ Aircraft maneuvering ⇒ safe separation

◆ Helo rotor downwash ⇒ miss at min range

◆ Aircraft bay acoustics ⇒ missile factor of safety

◆ Aircraft bay vibration ⇒ missile factor of safety

Figure 11. Precision Strike Missile/Aircraft Launch Integration Considerations.
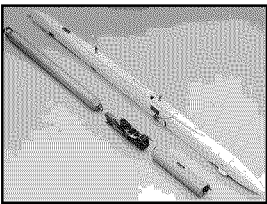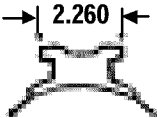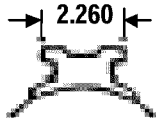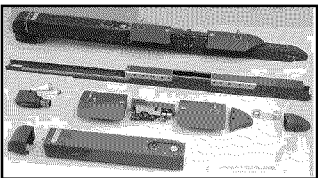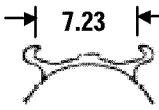
Table 2. MIL-STD-8591 Ejection Launcher Requirements.

Store Weight / Parameter	30 Inch Suspension	14 Inch Suspension
◆ Weight Up to 100 lb	Not Applicable	Yes
• Lug height (in)		0.75
• Min ejector area (in x in)		4.0 x 26.0
◆ Weight 101 to 1,450 lb	Yes	Yes
• Lug height (in)	1.35	1.00
• Min lug well (in)	0.515	0.515
• Min ejector area (in x in)	4. 0 x 36.0	4.0 x 26.0
◆ Weight Over 1,451 lb	Yes	Not Applicable
• Lug height (in)	1.35	
• Min lug well (in)	1.080	
• Min ejector area (in x in)	4.0 x 36.0	
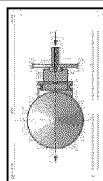
Ejection Stroke ⇩
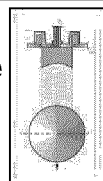
Rail Launcher	Forward Hanger	Aft Hanger
LAU-7 Sidewinder Launcher	→| 2.260 |←	→| 2.260 |←
LAU 117 Maverick Launcher	→|1.14|←	→| 7.23 |←

Note: Dimensions in inches.

• LAU 7 rail launched store weight and diameter limits are < 300 lb, < 7 in

•LAU 117 rail launched store weight and diameter limits are < 600 lb, < 10 in

Figure 12. MIL-STD-8591 Rail Launcher Examples.
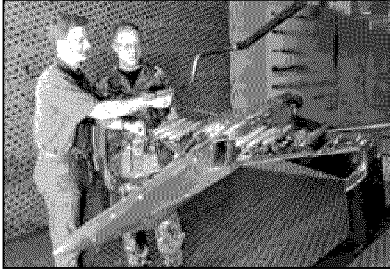
F-18 Store Compatibility Test in AEDC 16T
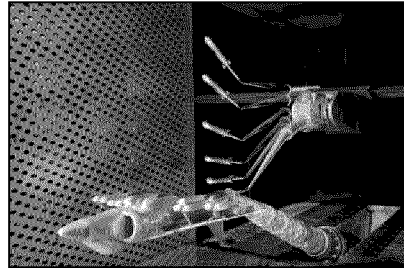
AV-8 Store Compatibility Test in AEDC 4T

Types of Wind Tunnel Testing for Store Compatibility
- Flow field mapping with probe
- Flow field mapping with store
- Captive trajectory simulation
- Drop testing
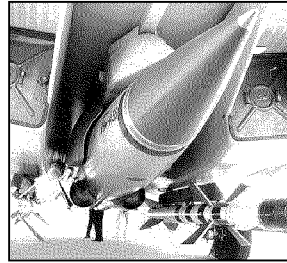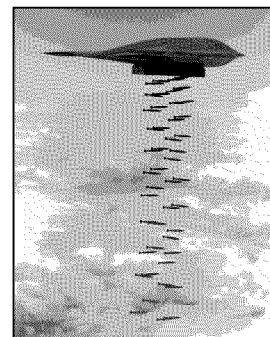

Example Stores with Flow Field Interaction: Kh-41 / AA-10

Figure 13. Store Separation Wind Tunnel Tests Are Required for Missile/Aircraft Compatibility.

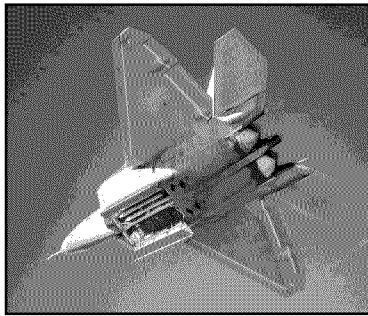AMRAAM Rail Launch from F-16

Laser Guided Bombs Drop from F-117

Rapid Bomb Drop from B-2

Figure 14. Examples of Safe Store Separation.

Center Weapon Bay Best for Ejection Launchers
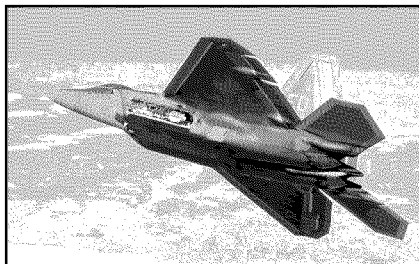

F-22 Bay Loadout: 2 AIM-120C, 1 GBU-32

F-117 Bay Loadout: 1 GBU-27, 1 GBU-10
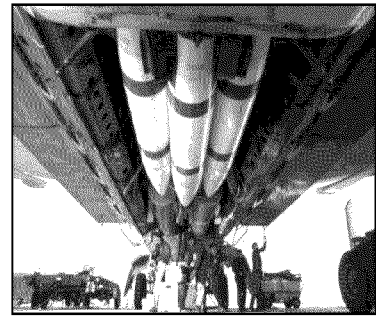
B-1 Bay Loadout: 8 AGM-69

Side Weapon Bay Best for Rail Launchers

**F-22 Side Bay Loadout: 1 AIM-9**

RAH-66 Side Bay Loadout: 1 AGM-114, 2 FIM-92, 4 Hydra 70

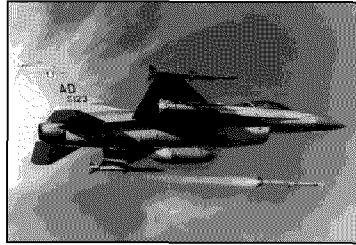Figure 15. Weapon Internal Bay Carriage and Loadout Examples.

Table 3. Minimum Smoke Propellant Has Low Observables.

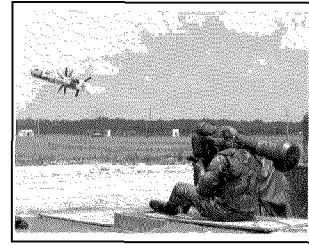| Type	I_{SP}, Specific Impulse, sec	ρ, Density, lb / in³	Burn Rate @ 1,000 psi, in / sec	Hazard	Observables
Min Smoke. No Al fuel or AP oxidizer. Nitramine XLDB (CL-20, ADN, HMX, RDX). Very low contrail (H_2O).	– / 220 - 255	– / 0.055 - 0.062	○ / 0.25 - 1.0	–	◓
Reduced Smoke. No Al (binder fuel). AP oxidizer. Low contrail (HCl)	○ / 250 - 260	○ / 0.062	◓ / 0.1 - 1.5	○	○
High Smoke. Al fuel. AP oxidizer. High smoke (Al_2O_3).	◓ / 260 - 265	◓ / 0.065	● / 0.1 - 3.0	◓	–

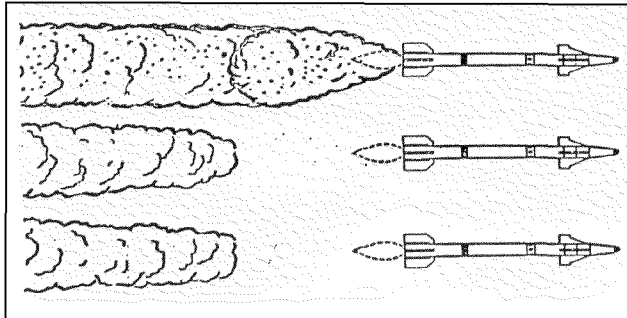● **Superior**   ◓ **Above Average**   ○ **Average**   – **Below Average**
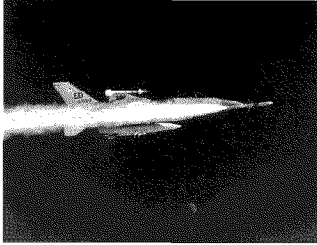
High Smoke Example: AIM-7   Reduced Smoke Example: AIM-120   Minimum Smoke Example: Javelin

High Smoke: Particles (e.g., metal fuel) at all atmosphere temperature.

Reduced Smoke: Contrail (HCl from AP oxidizer) at < -10° Fahrenheit atmospheric temperature.

Minimum Smoke: Contrail (H_2O) at < -35° Fahrenheit atmospheric temperature.

Figure 16. Minimum Smoke Propellant Has Low Observables.

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